TESTING OF EXPERT NOSE MATERIAL AND SENSOR HEADS IN THE DLR ARCJET FACILITIES

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ABSTRACT

EXPERT is a mission to gather in-flight data of the re-entry aerothermodynamic environment. The Nose Assembly (NAP) is a sub-system of the EXPERT vehicle, consisting of the CMC nose cap and embedded payloads, which are PL1 (FADS with RAFLEX sensor head), PL10 (RESPECT) and PL2 (PYREX). The behaviour of the C/C-SiC nose material and the payload sensor heads was investigated in different conditions in the L3K arc heated facility at DLR in Cologne. RESPECT and RAFLEX are using C/C-SiC sensor head bolts with holes that serve the purpose of pressure measurement (RAFLEX) and optical access to the plasma (RESPECT). Qualification models were tested to investigate the influence of hole and bolt edge. Test results will be presented and discussed versus results of predictions.

1. MISSION OVERVIEW

EXPERT will be launched on a sub-orbital trajectory with a peak velocity of 5 km/s. The maximum altitude will be approximately 120 km. During re-entry the peak heat flux will reach up to 1.5 MW/m² in the stagnation area assuming a partial catalytic behaviour of the Ceramic Matrix Composite (CMC) material of the nose. Since EXPERT is a ballistic vehicle with a relatively high ballistic coefficient the aerodynamic pressure in the stagnation area reaches a value of 1.5 bar [1]

2. NAP PAYLOADS

On EXPERT a total of 14 payloads (PL) will be installed. Of these, three are located in the Instrumented Nose Assembly (NAP) and one is situated at the boundary of the (CMC) nose to the metallic Thermal Protection System (TPS).

The three PLs in the NAP are PL1 Flush Air Data System (FADS) using the RAFLEX sensor head, PL2 Nose Heating with the PYREX measurement system and PL10 Shock Layer Chemistry employing the RESPECT spectroscopic experiment. Since PL2 is measuring the temperature of the CMC nose on the inside and is by design not getting into contact with the flow around the nose, it is not discussed in this paper. Fig. 1 and Fig. 2 show the location of the PL1 and PL10 sensor heads on EXPERT.

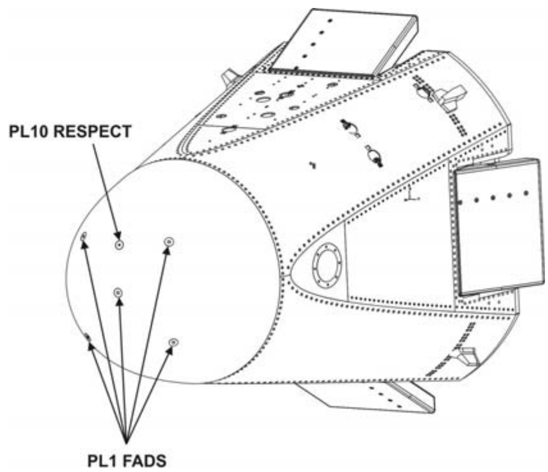

Figure 1: Location of PL1 and PL10 sensor heads.

2.1. Payload Objectives

2.1.1. Payload 1 FADS

The main functional objective of PL1 is to gather flight data like dynamic pressure, heat flux and vehicle movement. Therefore the pressures and temperatures at five different positions on the TPS nose shall be measured. The free flight dynamic pressure will be derived quite easily from the measured stagnation point pressure. The heat flux at each position shall be deduced from the measured temperature rise dT related to the flight time steps dt and the material / geometric data of the copper calorimeter.

The vehicle movement respectively the angle of attack (α) and the slip angle (β) variation over the flight time shall be deduced from the measured pressures of the four probes at the circumference (inclined 45°) normalized with the stagnation pressure and geometric data of the installation position.

2.1.2. Payload 10 RESPECT

The thermal and mechanical loads onto a space vehicle surface during re-entry are mainly defined by the high enthalpy flow state and its chemical composition close to the wall. One way to gain the information about these quantities is given by emission spectroscopic measurements during the re-entry flight. The main goal is to obtain more detailed information about the flow state in the post shock regime of a re-entry vehicle by measuring the spectrally resolved radiation onto the surface. Therefore a sensor design has to be chosen which enables spectral measurement of the post shock regime, which means in detail that a spectrometer based sensor system with optical access to the high enthalpy flow is essential [2].

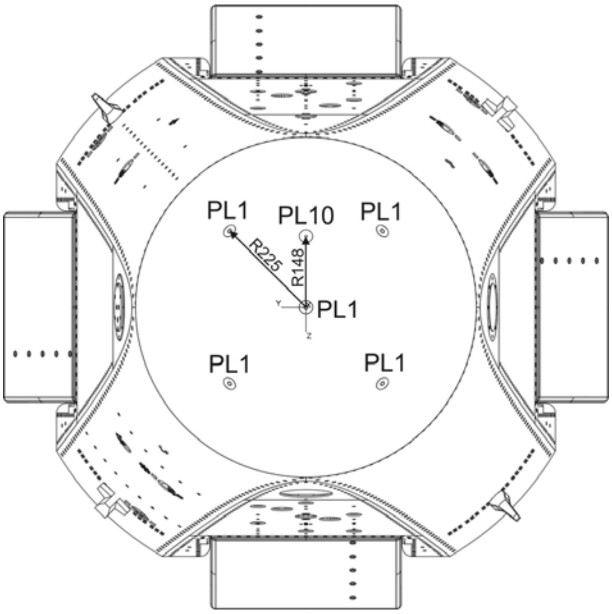

Figure 2: EXPERT front view with PL1 and PL10 locations.

2.2. Design of Payload 1 FADS Sensor Head

The sensor head of PL01 is called RAFLEX. It is a combined metallic and CMC design because RAFLEX gets into direct contact with the ultra-hot nose.

Similar to the design of the PL10 window assembly, a CMC bolt with countersunk head is inserted into the nose from outside of the nose. It is pulled into the countersunk hole via a spring assembly. Also in that case the spring has to be protected from excessive temperatures and it is moved away from the nose surface to use transient effects. The distance to the nose is covered by a TZM tube which is a molybdenum alloy. The actual calorimeter is located inside of the CMC bolt. However, it only has mechanical contact to the bolt at its rear end where temperatures stay relatively low. Between calorimeter and bolt, a copper tube creates two circumferential gaps to provide for a radiation shield in order to help keep the calorimeter temperatures acceptable.

The calorimeter features a central orifice where the pressure is obtained and routed to an internal pressure transducer that generates the electrical data signal. The heat flux onto the calorimeter is calculated from the temperature increase in the copper which is measured via two thermocouples. Fig. 3 shows a cross section of a FADS sensor head.

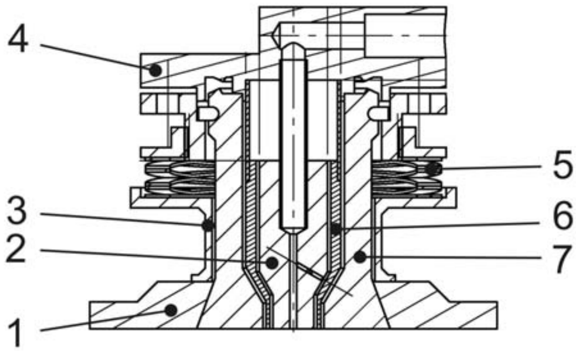

Figure 3: Cross section through the FADS sensor head.
1 CMC Nose 2 Calorimeter 3 TZM tube 4 Steel back plate 5 Spring 6 Radiation shield 7 CMC bolt

2.3. Payload 10 Shock Layer Chemistry

All components of the window are manufactured from C/C-SiC, except for two metallic springs. A threaded bolt is inserted into the nose from the outside and fixed via a nut. The nut is located at the far end of the bolt. It acts against a tube that spans the distance to the inner face of the CMC nose. In order to achieve always sufficient axial force in the bolt to hold it in place in the nose under any thermal condition, a metallic spring was included in the design between the nut and the distance tube.

In order to achieve a higher degree of inherent safety, the window was designed as a two-pane window, using two individual sapphire discs back to back. The sapphire discs are inserted in the CMC bolt from the back end. They are held in place via the nut and a distance bushing. Also in this case a metallic spring is used. Between the two sapphire discs and between them and the ceramic parts, graphite foil seals are used.

The material choice for the actual window was made very early in the design process. Sapphire was selected because it has favourable properties with regard to the use at high temperatures. Sapphire can be used up to approximately 1000°C for optical purposes. Above that the optical properties degrade and the transmissibility is reduced. However, the melting temperature is at 2000°C which is almost as high as the maximum surface temperatures of the nose itself.

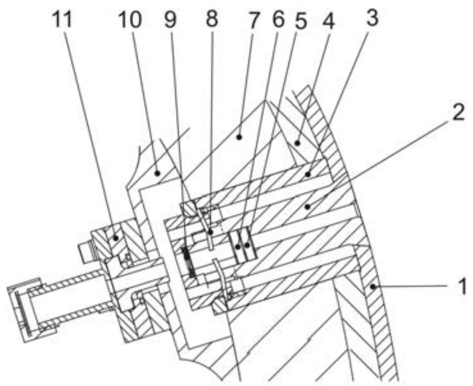

Figure 4: Cross section through the PL10 window.

1 CMC nose, 2 CMC bolt, 3 CMC distance tube, 4 High temperature insulation, 5 Sapphire disc 1, 6 Sapphire disc 2, 7 Medium temp. insulation, 8 Spring, 9 Spring, 10 Colander, 11 Sensor head

Due to the high surface temperatures in relation to the sapphire properties, the window can not be located at the surface of the CMC nose. It had to be put in a place where temperatures stay below 1000°C as a design requirement.

The mechanical design of the window takes that into account. Fig. 4 shows a cross section of the window assembly with its components. Fig. 5 is an exploded view of the parts. It can be seen that the sapphire window is located at a distance of roughly 40 mm from the outer surface of the CMC nose. The design works in this way due to the fact that the heat load is highly transient and there is no phase of a thermal steady-state condition in the nose and the associated parts.

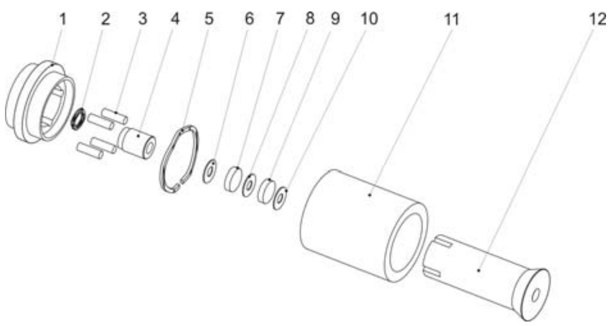

Figure 5: Exploded view of the window assembly.

1 CMC nut, 2 Spring, 3 Lock pins, 4 Bushing, 5 Spring, 6 Graphite seal, 7 Sapphire disc, 8 Graphite seal, 9 Sapphire disc, 10 Graphite seal, 11 Distance tube, 12 Bolt

3. NUMERICAL PREDICTIONS

3.1. Payload 1

The FADS sensor head was analysed numerically to determine the internal temperature field. The essential issue in the lay-out was the sizing of the copper calorimeter and to prevent melting. It has to store the thermal energy that it receives during the whole mission since also a heat transfer to the internal structures has to be avoided.

Fig. 6 shows the temperature transients that were calculated. The six major components will be discussed here. It can be noted that even though the CMC bolt is in direct contact to the nose, it reaches a maximum temperature of 1800°C on the surface of the bolt head which is more than 300°C lower than that of the nose. This is a clear indication of the highly transient nature of the mission during which the sensor head assembly never reaches a steady-state but where the CMC bolt is a heat sink in the nose. The TZM tube goes up to 1400°C and thus stays below its use limit temperature. The spring is placed at the rear end of the TZM tube and is considerably lower in temperature. The peak value observed there is close to 800°C. The radiation shield and the steel tube at its back end are very close together and go up to roughly 750°C.

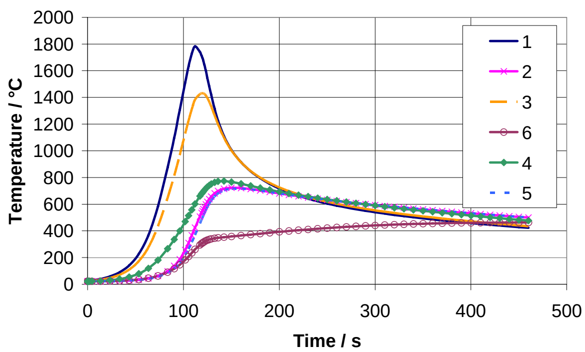

Figure 6: Temperatures in the FADS sensor head obtained via FEA.

1 CMC bolt surface, 2 Radiation shield, 3 TZM tube,4 Spring, 5 Steel, 6 Calorimeter

The calorimeter itself shows a slightly different behaviour due to the design of the sensor head. Its temperature rise is slower and does not show the distinct peak as the graphs of the other components that were evaluated. At approximately 350°C the temperature increase slows down after the time of peak heating in the trajectory was reached but still continues up to 500°C when it crosses the graphs of the other components that are already cooling down.

3.2. Payload 10

The lay-out of PL10 on EXPERT requires direct optical access to the shock layer surrounding the vehicle. There are two main challenges that had to be overcome during the development, which are the extremely high temperature and the relatively high dynamic pressure.

The temperature on the CMC nose of the capsule was calculated using FEA. The peak value in the stagnation region is roughly 2150°C. Interestingly, the maximum temperature does not appear in the stagnation point itself, but in a circular area surrounding it. The location of the PL10 window is close to that area of maximum temperature.

In the case of the window assembly for PL10 it can be noted that the peak temperature of the CMC bolt surface of roughly 2050°C is closer to the peak temperature that can be observed on the nose than it is the case with the PL01 sensor heads. The reason is that the window is sitting right in the region of maximum heat flux on the nose whereas the PL01 sensor heads are slightly below that.

In the case of the window assembly the essential issue was the sizing of the sapphire window temperature to keep it below 1000°C. The graph in Fig. 7 shows that the window reaches just 500°C in the prediction with FEA, thereby justifying the design.

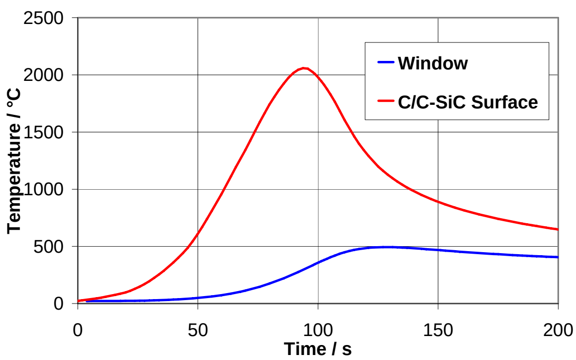

Figure 7: Predicted temperatures for the PL10 window assembly.

4. TEST RESULTS

4.1. Facilities

The tests were carried out in the L3K and L2K arc jet facilities of DLR in Cologne. The L3K facility is one of the two test legs of the DLR's arc heated facilities LBK. The setup of the LBK facility is schematically plotted in Fig. 8. The principal component of L3K is a segmented arc heater which offers a maximum electrical power of 6 MW. It is used to heat the working to high enthalpy conditions.

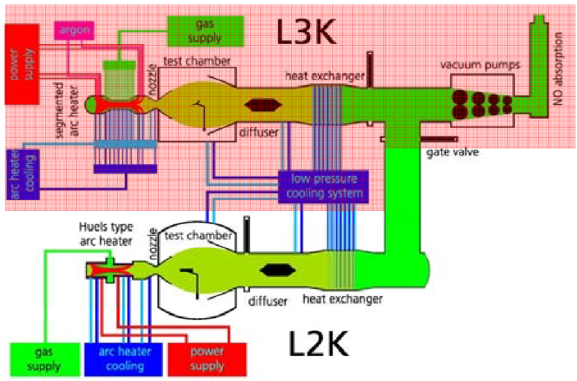

Figure 8: Schematic sketch of the LBK facility

After being heated the gas is accelerated to hypersonic flow velocities by means of a convergent-divergent nozzle. In L3K, throat diameters of 14 and 29 mm are available. The nozzle's expansion part is conical with a half angle of 12 deg. A modular design allows for various exit diameters of 50, 100, 200 and 300 mm. So, the facility setup can effectively be adapted to particular necessities of a certain test campaign. For stagnation point testing the maximal model diameter is 150 mm. Flat-plate models can be tested up to a width of 280 mm and a length of 300 mm.

The test chamber is directly connected to the nozzle exit. Inside the test chamber a hypersonic free jet is formed where specimen can be placed for testing. Depending on the nozzle configuration free stream Mach numbers between 3 and 10 can be achieved. A more detailed description of the facility is given by Gülhan et al. [3, 4]. L2K uses large parts of the same infrastructure. It is characterized by a lower power level of up to 1.4 MW.

4.2. Payload 1 FADS

For the arc jet testing the test article was integrated in a Ø = 50mm standard probe holder. The probe was mounted on a moveable probe holder to move the probe in and out of the plasma jet during the tests. In addition a system has been used for the integrated probe/sensor head configuration.

Figure 9: Integrated PL1 system sample.

The RAFLEX system sample is shown in Fig. 9 and a cross section is shown in Figure 10.

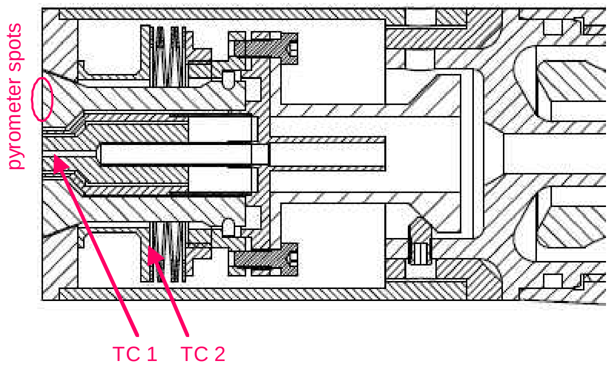

Figure 10: Cross section of the arc jet probe.

The function of the RAFLEX system was verified by measuring the Pitot pressure and by calculating the heat flux from the measured data.

The Pitot pressure was measured via the central orifice in the calorimeter. The measured values are shown in Fig. 11. The value of 148 mbar corresponds very well to the value of 146 mbar that was acquired before the test with the standard Pitot probe of the facility. It can be noted that the pressure signal is very steady over the entire test.

The heat flux was calculated by evaluating the temperature increase of the calorimeter mass over time using the thermal properties of copper. The result is shown in Fig. 12 for a test carried out in L2K. The facility parameters were chosen to get a heat flux level of 1.4 MW/m² for that type of material. It can be seen that the measured value is between 1.3 and 1.4 MW/m² over the entire test duration.

No evidence of leakage could be detected for all tests that were carried out with the RAFLEX sensor head.

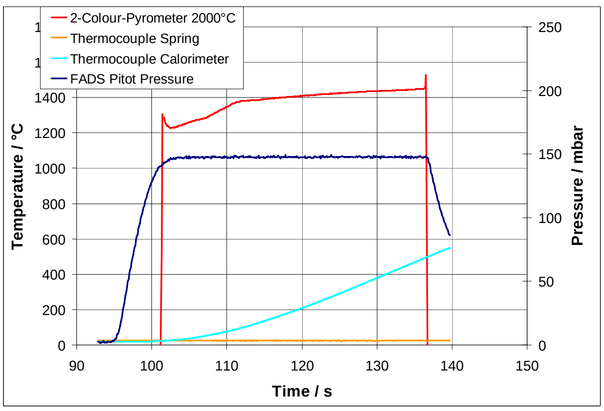

Figure 11: RAFLEX test data.

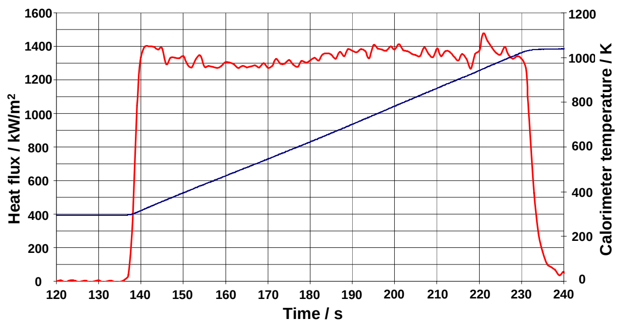

Figure 12: Measured heat flux of PL1 sensor head.

4.3. Payload 10 RESPECT

Similar to the tests of PL1 the tests of the RESPECT window assembly were carried out using a 50 mm setup. The assembled L3K test probe is shown in Fig. 13. The bright-coloured ring on the circumferential edge of the probe is a ceramic adhesive to apply extra protection at the edge of the sample.

Figure 13: RESPECT arc jet system sample.

The test results are shown in Fig. 14. In steady-state condition of the L3K flow the surface temperature of the probe rises to 1900°C at the end of the test. The temperature inside the assembly was recorded in several locations. Directly behind the sapphire windows the temperature was measured. A maximum value of 640°C was recorded.

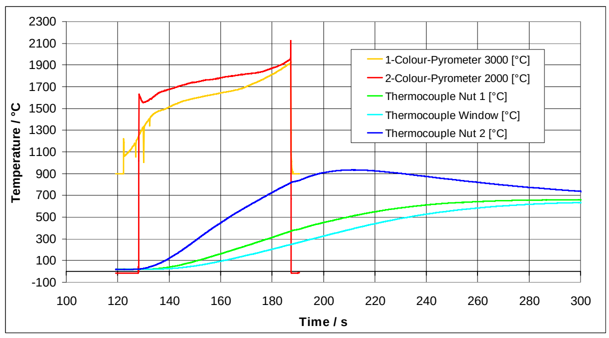

Figure 14: RESPECT measured temperatures.

After the test no evidence of leakage could be detected which means that no hot gas had entered inside the test assembly. That was the case for all tests with the window assembly.

4.4. Effect of a drill hole/circular edge on the nose

During aerothermal testing of the system samples infra-red data was collected which is shown in Fig. 15 – 17.

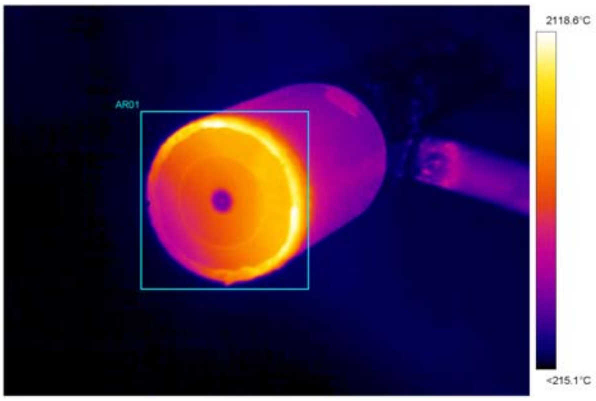

Figure 15: System sample RAFLEX [076074L].

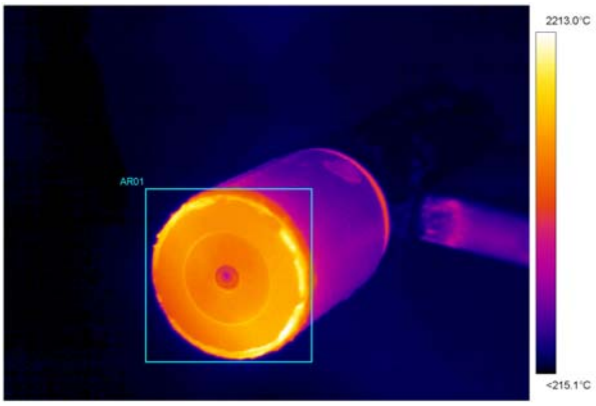

Figure 16: System sample RAFLEX [077074L].

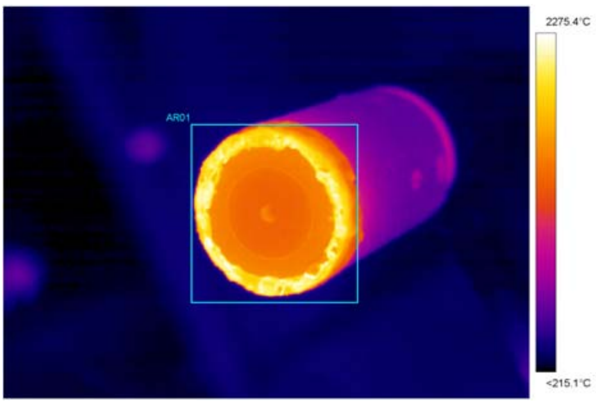

Figure 17: System sample RESPECT [070074L]

With this infrared data it is possible to create a temperature profile over the cross sectional area of the system sample. The following graphs (Fig.18 and 19) show the temperature profile from the left to the right edge and from the top to the bottom edge which are created from the infra-red data images.

Both figures show clearly the intersection from the nose cap material to the bolt edge and to the bolt center hole. The increased temperatures at the outer circular edge of the test sample can be neglected, because this edge will not be present in the flight model. So the increase of the temperature at the outer circular edge won't occur in real flight conditions.

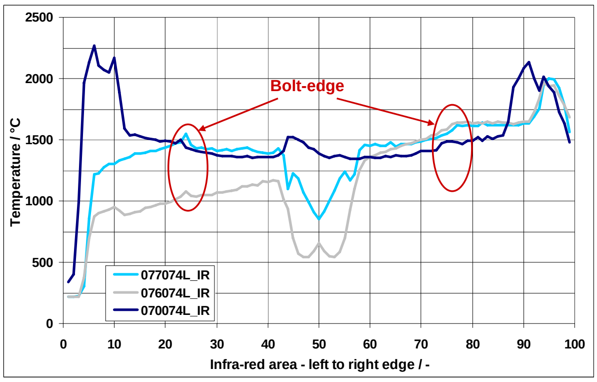

Figure 18: Temperature profile – left to right edge.

Both diagrams show clearly that there are no significant temperature changes at the bolt edge.

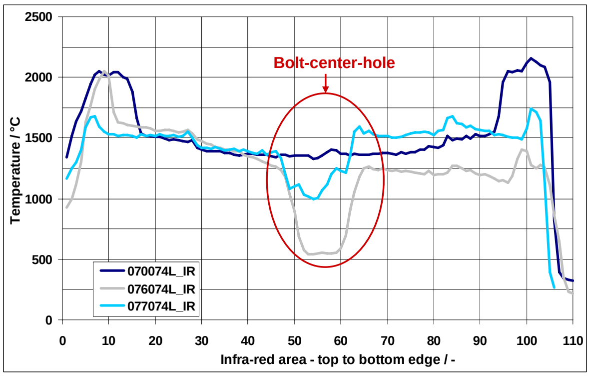

Figure 19: Temperature profile – top to bottom edge.

The bolt center holes for the RAFLEX system samples [076074L] and [077074L] show a significant reduction of temperature. This is due to two effects. On the one hand side lower temperature values are reached in the copper calorimeter in comparison to the CMC surface by design. On the other hand the infrared measurement was based on the emissivity values for the CMC material which are higher than for copper. Thus, the RAFLEX infrared images can only be used for qualitative assessments.

In the case of RESPECT there is only a slight increase of temperature at the area of the bolt-center-hole which can be explained by a reduced amount of re-radiation in the hole.

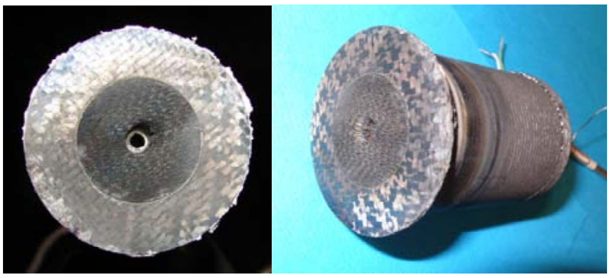

Figure 20: RESPECT [023084L] after testing – T_{max}= 2500°C.

Further tests pointed out that the increase of temperature has no destroying effect on the experiment. Fig. 20 shows the RESPECT window assembly after testing at up to 2500°C. The following detail image (Fig. 21) shows the smooth transition of the material from bolt head to the surrounding material (nose cap). No step or gap formation could be observed at the bolt edge, so it is no trigger for starting oxidation or erosion on the CMC nose.

Figure 21: RESPECT [023084L] after testing – T_{max}= 2500°C.

5. CONCLUSION

A number of tests were carried out with system samples of the EXPERT payloads PL1 and PL10 in the L2K and L3K facilities of DLR. The functional performance of the sensor heads could be verified successfully.

In addition the tests showed that the circular bolt edge has no negative influence on the performance of the CMC nose. Moreover, also the center hole edge of the RESPECT bolt does not affect the behaviour of the window system.

6. REFERENCES

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